Higgsless and Higgsful Standard Model with Spontaneous Dimensional Reduction and LHC Signatures

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Outline

1. Why Higgs Boson ?
2. Longitudinal WW Scattering in SM
3. Spontaneous Dimensional Reduction
4. Unitary Higgsless SM under SDR: WW Scattering
5. Unitary Cross Sections of WW Scattering
6. Unitary Higgsful SM under SDR
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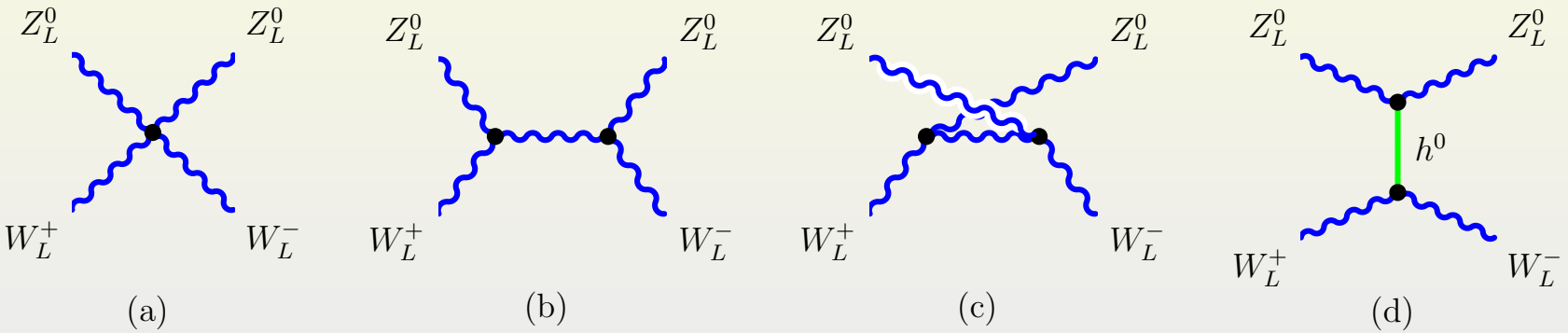
Why is Higgs Boson crucial in the SM ?

- Ensure Perturbative Renormalizability of the SM
- Ensure Perturbative Unitarity of the SM
- Mass Generation for W/Z and Fermions
- In fact, Cornwall-Levin-Tiktopoulos (1974) showed that only Renormalizable gauge theories with spontaneous symmetry breaking (such as SM) can have perturbative tree-level Unitarity.

Unitarity of WW Scattering

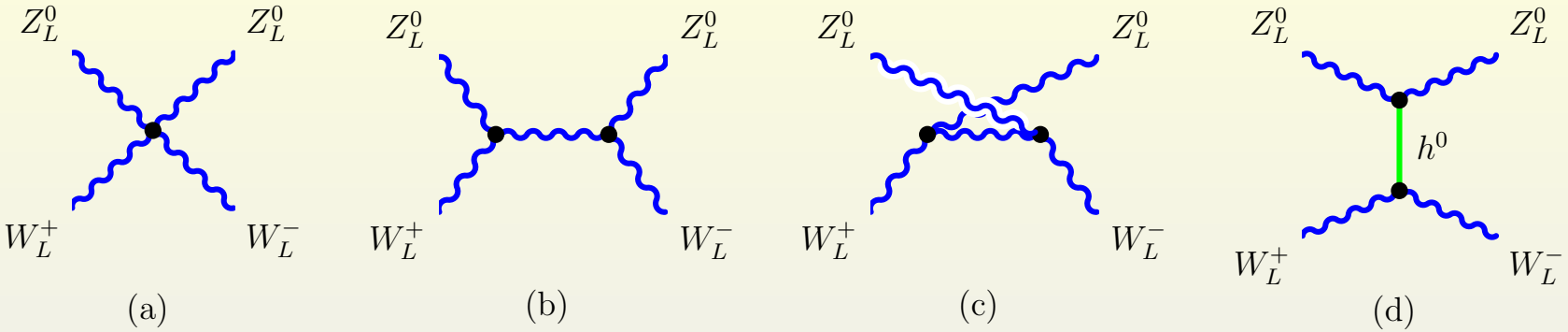


- **At high energies $E \gg M_W$, Longitudinal Polarization of W (Z) boson is proportional to its 4-momentum,**

$$\epsilon_L^\mu \propto k^\mu / M_W$$

- **Hence, each diagram has the form:**

$$\mathcal{T} = A \cdot E_{cm}^4 + B \cdot E_{cm}^2 + \mathcal{O}(E_{cm}^0)$$



$$\mathcal{T} = A \cdot E_{\text{cm}}^4 + B \cdot E_{\text{cm}}^2 + \mathcal{O}(E_{\text{cm}}^0)$$

- **In conventional 4d SM, perturbative Unitarity requires $\mathcal{O}(E_{\text{cm}}^4)$ and $\mathcal{O}(E_{\text{cm}}^2)$ terms to exactly cancel.**
- **$\mathcal{O}(E_{\text{cm}}^4)$ cancelation is ensured by YM gauge structure.**
- **$\mathcal{O}(E_{\text{cm}}^2)$ cancelation is ensured by Higgs boson of SM !**
- **But, "Higgs Boson" is not the only way to ensure perturbative Unitarity of SM !**

Spontaneous Dimensional Reduction (SDR)

- **Can Quantum Gravity (QG) play a key role in mass-generation ?**

- **SDR is a Nonperturbative QG Effect, indicating that Spacetime Dimensions get reduced towards 2 at high energies.**

  For reviews: S. Carlip, 0909.3329, 1009.1136

Spontaneous Dimensional Reduction (SDR)

- **Strikingly, various approaches to QG have revealed the similar phenomena of SDR ! E.g.,**

  Causal dynamical triangulation (Ambjorn et al, 2005),
  Exact renormalization group (Lauscher, Reuter, 2002),
  High temperature string theory (Atick, Witten, 1988),
  Horava-Lifshitz model (Horava, 2009), ...

- **Also motivated by Dimensional Deconstruction** (Arkani−Hamed, Cohen, Georgi, 2001)

- **No full theory of QG avaiable to uniquely compute all the details.**

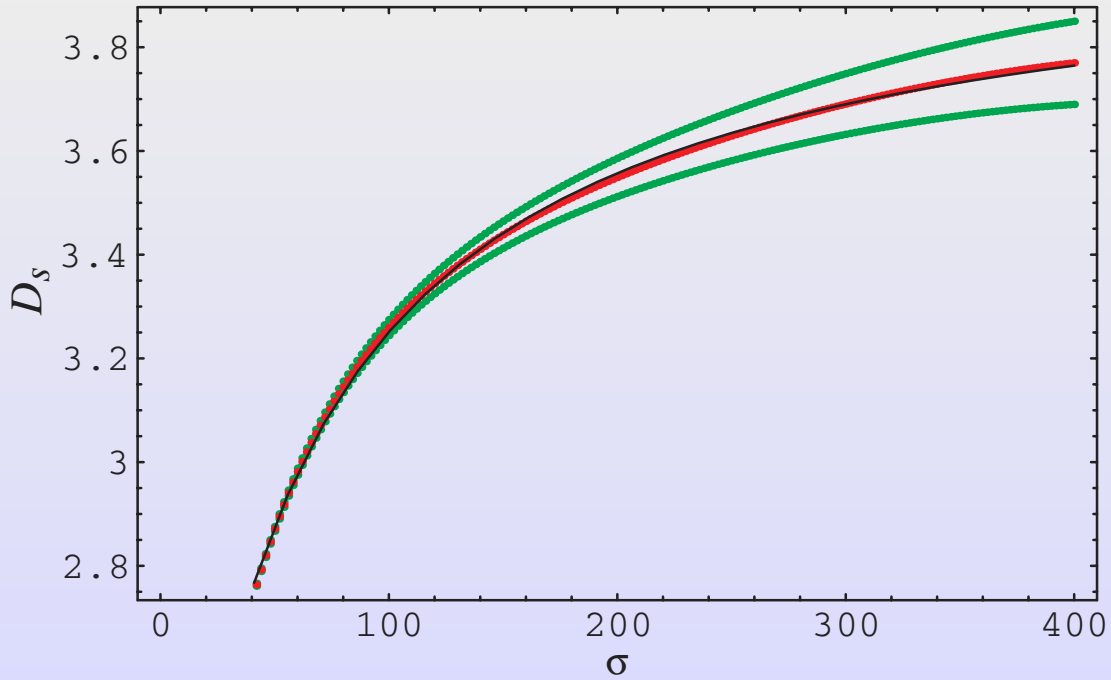
- **We'll construct Low Energy Effective Theory of SDR !**

E.g.: Causal Dynamical Triangulation (CDT)

- **Spectral dimension D_S as a function of diffusion time σ from CDT. Best numerical fit $D_S(\sigma) = 4.02 - 119/(54+\sigma)$.**

(J. Ambjorn et al, PRL.95(2005)171301)

- **Prediction: $\mathbf{D_S(\sigma = 0) = 1.80 \pm 0.25}$, compatible with $\mathbf{D_S = 2}$.**



Effective Dimensional Flow under SDR

- **Spacetime dimensions undergoes a continuous reduction as energy scale increases.**
- **Parameterize spacetime dimension $\mathbf{n = n(\mu)}$ as a function of energy scale μ.**
- **Key feature of $\mathbf{n = n(\mu)}$,**

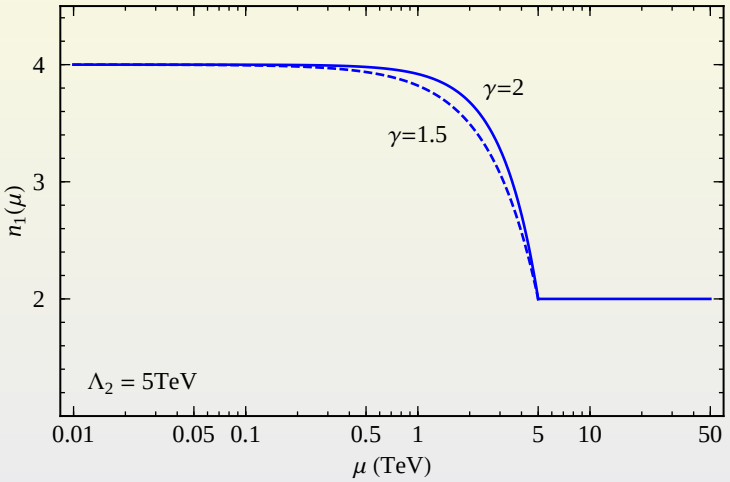
$$n \to 4 \quad \textbf{as} \quad \mu \to 0\,,$$

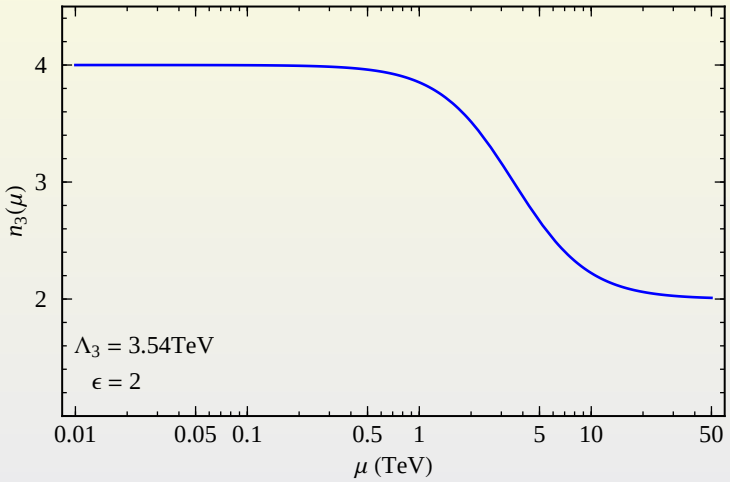
$$n \to 2 \quad \textbf{as} \quad \mu \to \Lambda_{\mathbf{UV}}\,,$$

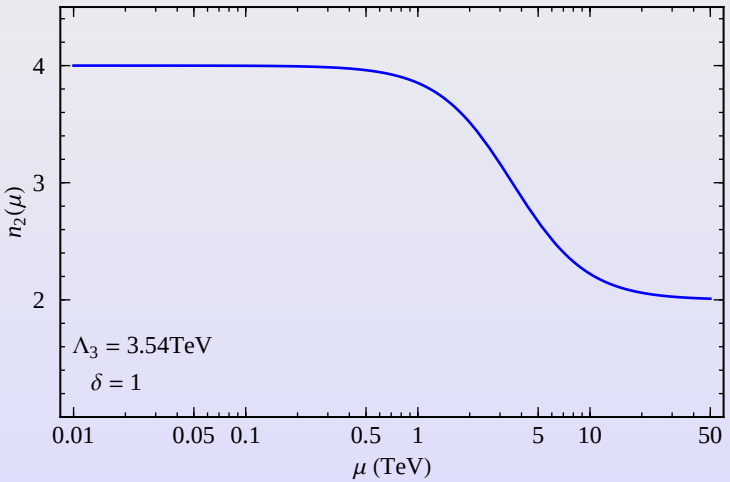
where $\Lambda_{\mathbf{UV}}$ is the UV cutoff for SDR above which full QG will take effect.

- **$\Lambda_{\mathbf{UV}}$ may be low and lies at TeV Scale.**

Effective Realizations of Dimensional Flow







$$n_1(\mu) = 4 - 2\left(\frac{\mu}{\Lambda_2}\right)^{\gamma}$$

$$n_2(\mu) = 3 - \tanh\log\left(\frac{\mu}{\Lambda_3}\right)^{\delta}$$

$$n_3(\mu) = 4 - \frac{2}{1+(\Lambda_3/\mu)^{\epsilon}}$$

- He and Xianyu, 1112.1028 and 1207.nnnn (to appear)

Construction of Effective EW Theory under SDR

- **Calcagni** $(\mathrm{arXiv}:1107.5041)$ **gave systematical treatment of action** S**, constructed such that the Lagrangian** $\mathscr{L}$ **lies in 4d and respects usual 4d Lorentz symmetry, while SDR is governed by properly defined measure** $\mathrm{d}\rho$**.**

- **Intuitively, this is similar to conventional Dimentional Reduction Regularization Method, which maintains 4d Lorentz symmetry and continues physics to** $n<4$**.**

- **For current tree-level study, detailed math-structure is irrelevant. We'll denote** $\mathrm{d}\rho$ **by** $\mathrm{d}^n x$**, where** n **is a function of energy scale** μ**. The action may be written as,** $S=\int \mathrm{d}^n x\,\mathscr{L}$**. — We only need to compute** S**-matrix of Longitudinal** W_L **which is equivalent to that of scalar Goldstone, so it is manifestly Lorentz-invariant for any** n**.**

Construction of Effective EW Theory under SDR

- **The Lagrangian is just SM with Higgs boson removed. The gauge sector is:**

$$\mathscr{L} = -\frac{1}{4} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + M_W^2 W^+_\mu W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu$$

- **The Lagrangian has dimension $n(\mu)$, so the gauge coupling g has dimension $[g] = (4-n)/2$.**

- **We can always define a dimensionless gauge coupling $\tilde{g}$. Since the only mass-parameter appeared in $\mathscr{L}$ is M_W, so we have,**

$$g = \tilde{g} M_W^{(4-n)/2}$$

Construction of Effective EW Theory under SDR

- **Value of dimensionless gauge coupling $\tilde{g}$ is given by g at $n = 4$,**

$$g = \tilde{g} M_W^{(4-n)/2}$$

- **Under SDR, such a Higgsless SM behaves well in the UV region because $n(\mu) \to 2$ in the UV and it is (super)renormalizable.**

- **It is well-known that gauge-boson-masses can be naturally realized in lower dimensions, without invoking conventional Higgs mechanism.**

Construction of Effective EW Theory under SDR

- In 2d, the gauge boson has longitudinal polarization only, and thus must be massive. The 2d QED — Schwinger Model has the finite photon mass from radiative corrections, with $[e] = 1$,

$$m_\gamma^2 = \frac{e^2}{\pi}$$

- The 3d QED — Chern-Simons-Maxwell Theory has a massive photon as well, with the topological mass,

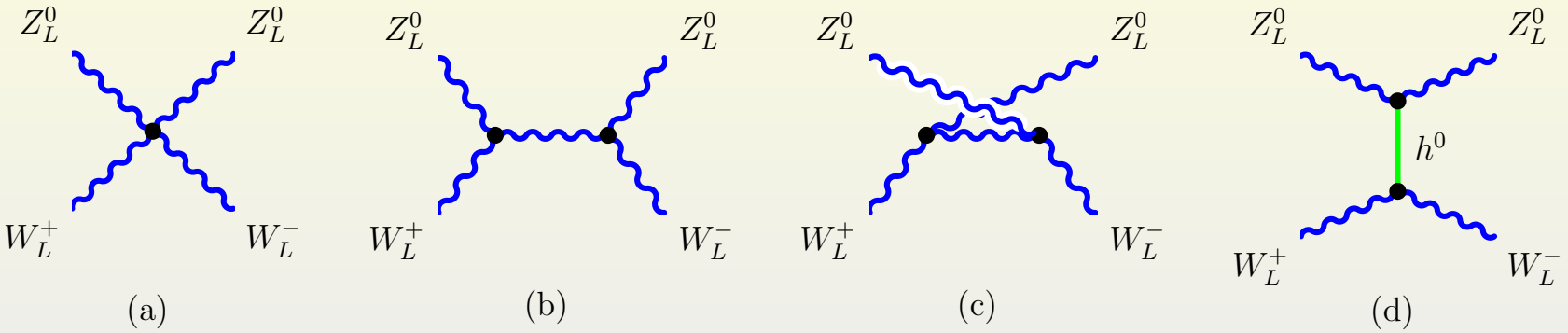
$$m_{\mathbf{cs}} = \kappa e^2$$

where κ is dimensionless Chern-Simmons coupling and $[e] = 1/2$.

Avoid Possible Lorentz Violation

- Our Lagrangian is manifestly Lorentz-invariant, defined in 4d.
- The construction of SDR in effective theory naturally maintains 4d Lorentz symmetry.
- This means that the dispersion relations for particles (such as photon) are not affected at tree-level. So it is free from Lorentz-violation-constraints of cosmic ray observations.
- We can reformulate SDR from Asymptotic Safety scenario (a la Weinberg) which has manifest 4d Lorentz symmetry from the start.

Partial Wave Unitarity of WW Scattering



- **Summing up the first three diagrams yields,**

$$\mathcal{T} = \frac{g^2}{4M_W^2} E_{\mathbf{cm}}^2 + \mathcal{O}(E_{\mathbf{cm}}^0)$$

- **Partial wave amplitude in n dimensions:**

$$a_\ell = \frac{E_{\mathbf{cm}}^{n-4}}{2(16\pi)^{n/2-1}\Gamma(\frac{n}{2}-1)\mathcal{C}_\ell^{(n-3)/2}(1)} \times \int_0^\pi \mathrm{d}\theta \, \sin^{n-3}\theta \, \mathcal{C}_\ell^{(n-3)/2}(\cos\theta)\mathcal{T}(E_{\mathbf{cm}}, \theta)$$

Partial Wave Unitarity: Coupled Channel Analysis

- **Only two channels contribute:** $\left|W_L^+ W_L^-\right\rangle$ **and** $\frac{1}{\sqrt{2}}\left|Z_L^0 Z_L^0\right\rangle$**:**

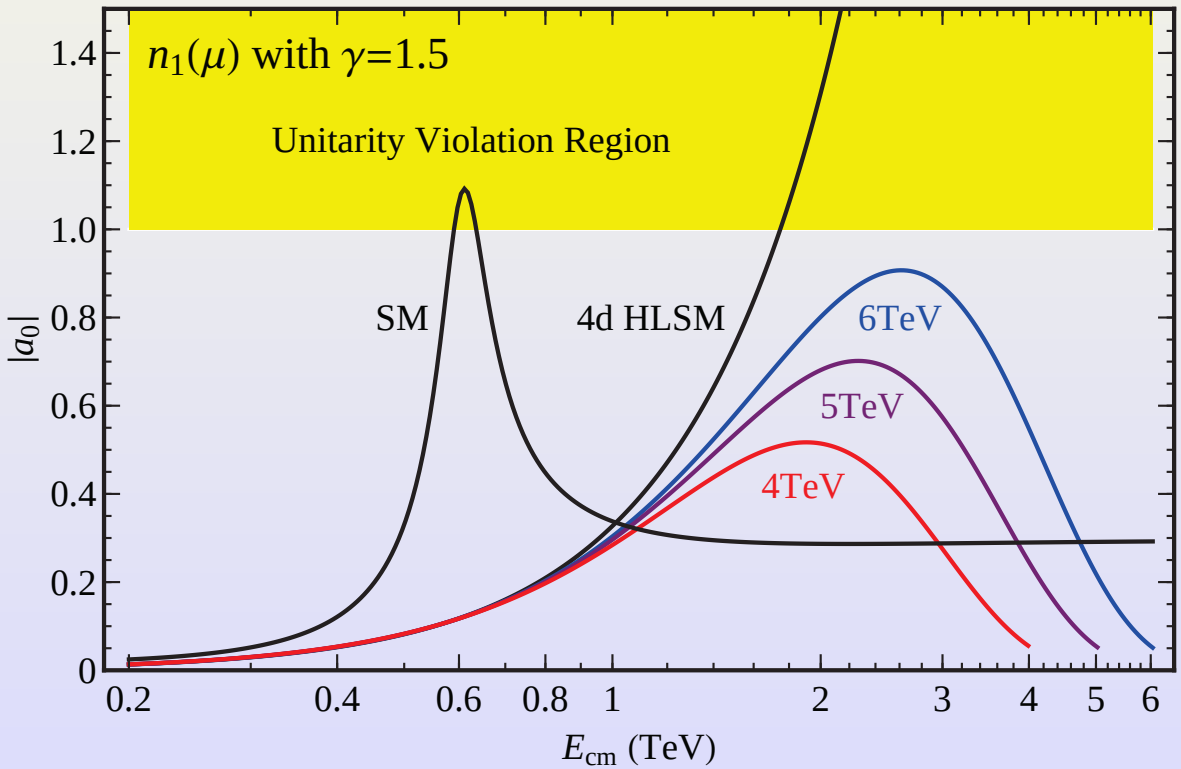
$$\mathcal{T}_{\mathbf{coup}} = \frac{g^2 E_{\mathbf{cm}}^2}{8M_W^2}\begin{pmatrix} 1+\cos\theta & \sqrt{2} \\ \sqrt{2} & 0 \end{pmatrix}$$

$$\Rightarrow \left|a_0^{\mathbf{max}}\right| = \frac{\tilde{g}^2}{2^{n+1}\pi^{(n-3)/2}\Gamma\left(\frac{n-1}{2}\right)}\left(\frac{E_{\mathbf{cm}}}{2M_W}\right)^{n-2}$$

- **Unitarity condition** $|a_0| \leqslant 1$ **remains unchanged in general dimension-**n**, but the phase space of partial wave integral changes.**

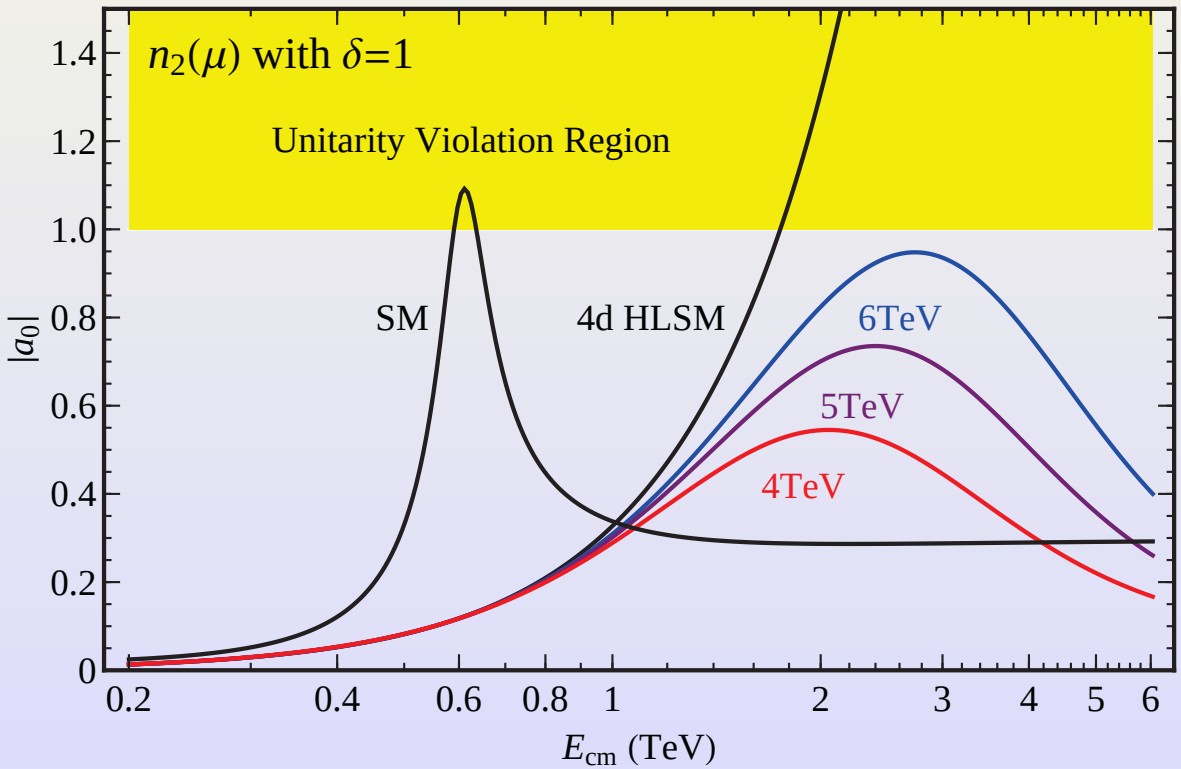
Partial Wave Unitarity under SDR with Flow $n_1(\mu)$

- **Partial wave amplitude $|a_0|$ as a function of energy $E_{\rm cm}$ for different UV Scale $\Lambda_{\rm UV} = 4,\, 5,\, 6\,{\rm TeV}$.**



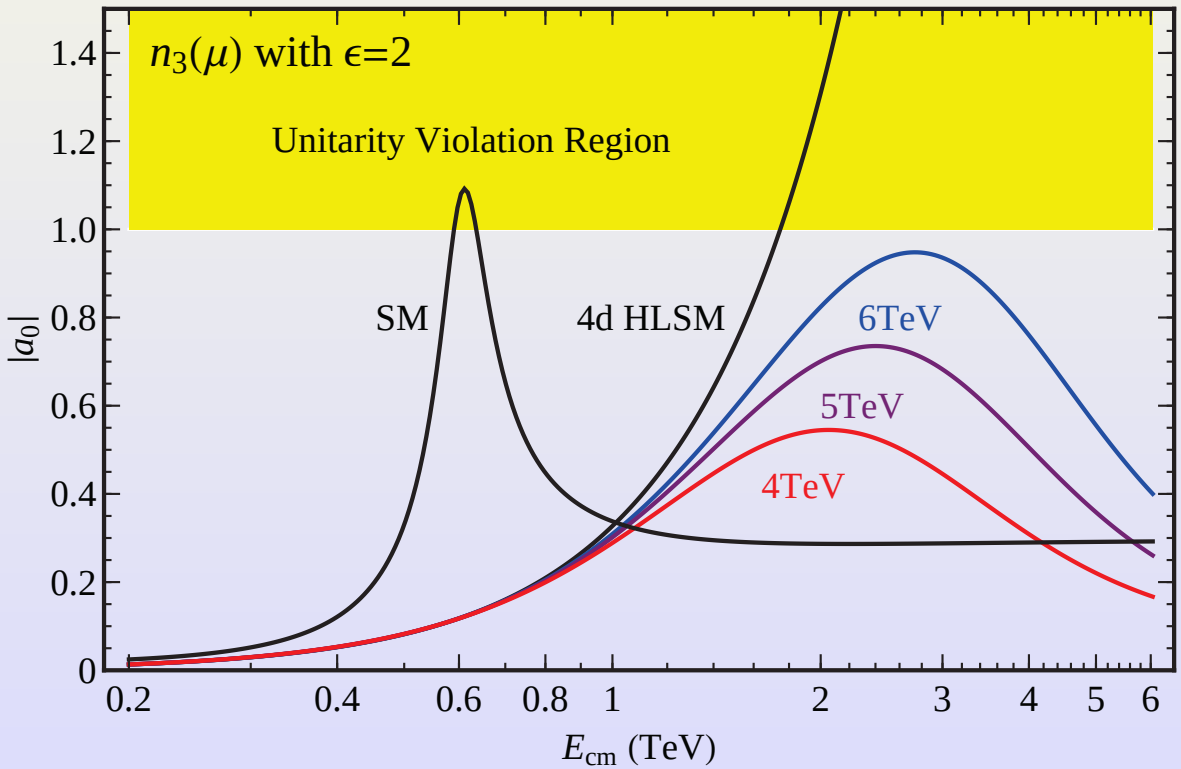
Partial Wave Unitarity under SDR with Flow $n_2(\mu)$

- **Partial wave amplitude $|a_0|$ as a function of energy $E_{\rm cm}$ for different UV Scale $\Lambda_{\rm UV} = 4,\, 5,\, 6\,{\rm TeV}$.**



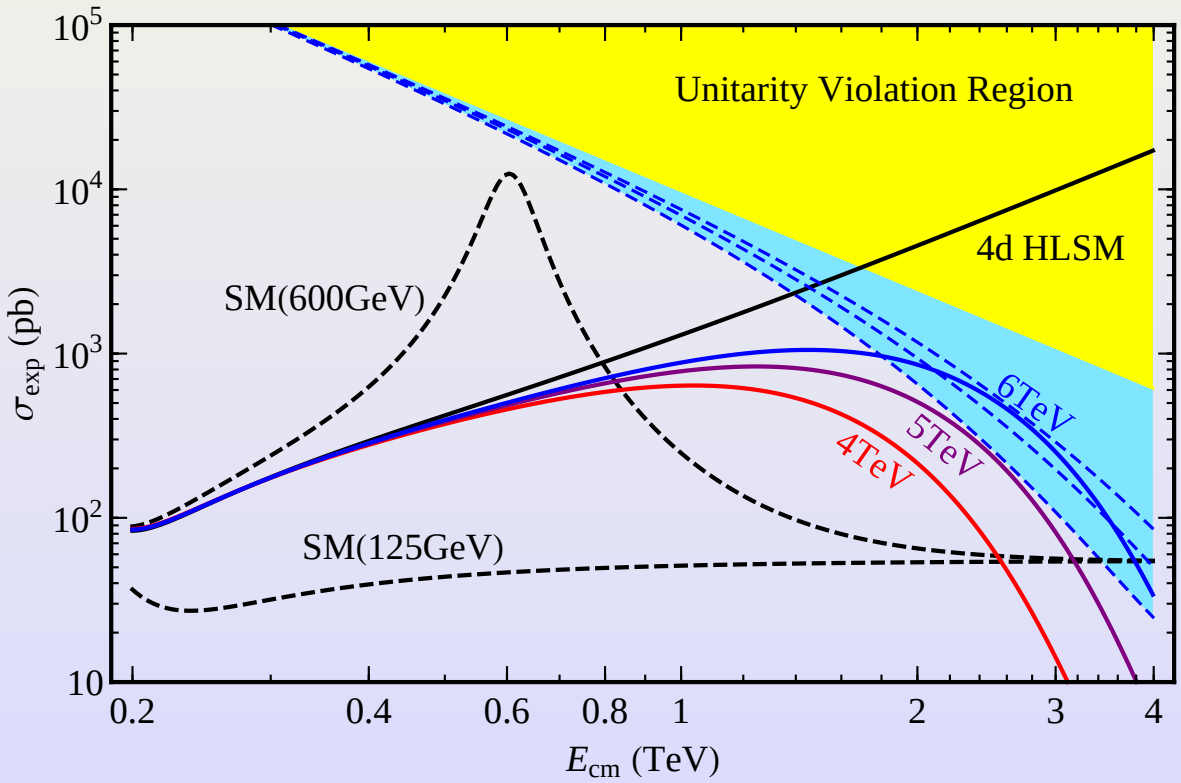
Partial Wave Unitarity under SDR with Flow $n_3(\mu)$

- **Partial wave amplitude $|a_0|$ as a function of energy $E_{\rm cm}$ for different UV Scale $\Lambda_{\rm UV} = 4,\, 5,\, 6\,{\rm TeV}$.**



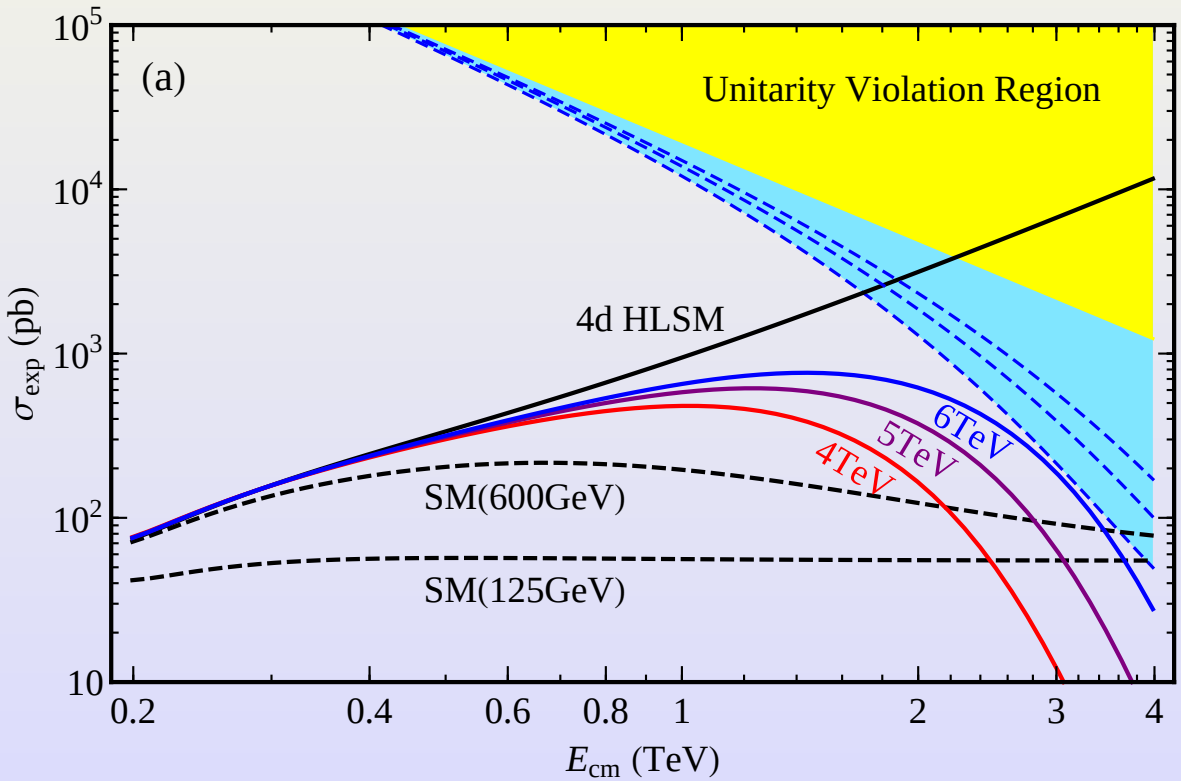
Unitary WW Cross Sections under SDR

- **Cross section for** $W_L^+W_L^- \to Z_L^0Z_L^0$
- **SDR generates a broad "lump" in 1-4 TeV region, which is universal in all channels.**



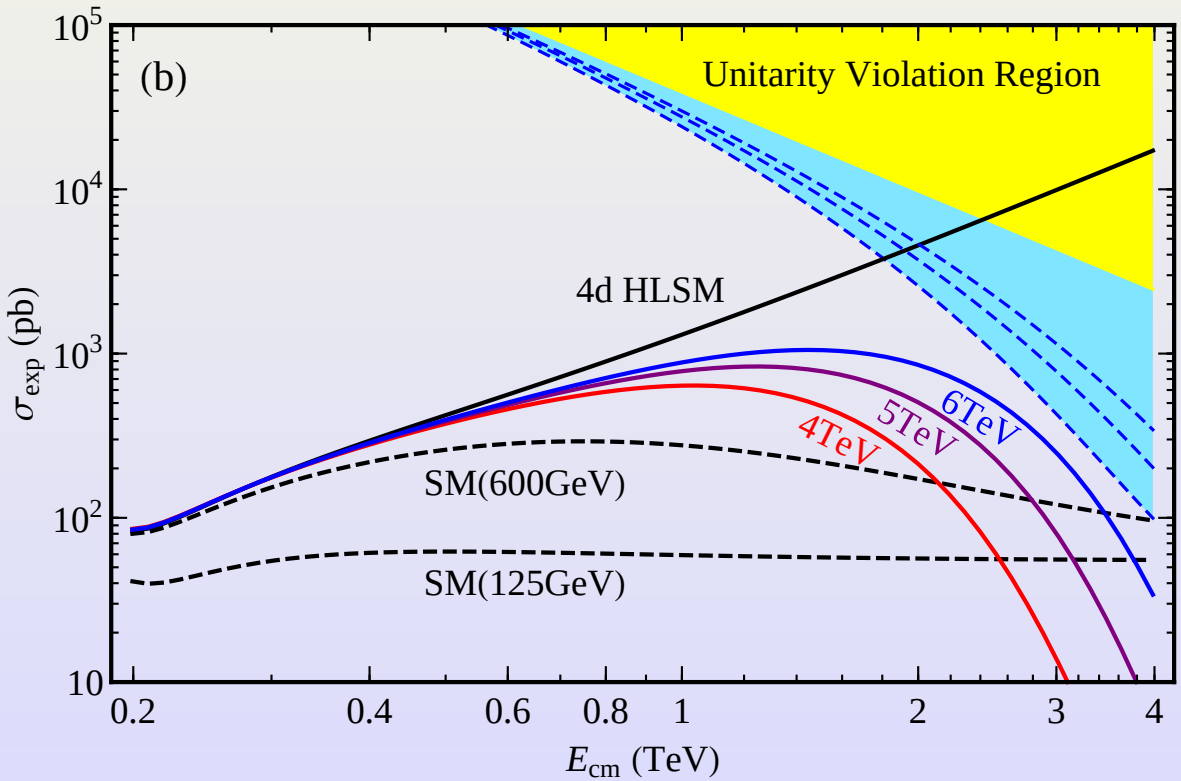
Unitary WW Cross Sections under SDR

- Cross section for $W_L^+ Z_L^0 \to W_L^+ Z_L^0$
- The broad "lump" in 1-4 TeV region is universal in all channels.



Unitary WW Cross Sections under SDR

- Cross section for $W_L^+W_L^+ \to W_L^+W_L^+$
- The broad "lump" in 1-4 TeV region is universal in all channels.



Unitary Higgsful SM under SDR

- **What happens if a light Higgs Boson (125 GeV) exists ?**

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Unitary Higgsful SM under SDR

- Under TeV Scale SDR: Higgsful SM is free from Hierarchy Problem !
- TeV scale quantum gravity effects can cause Anomalous Higgs Gauge Couplings,

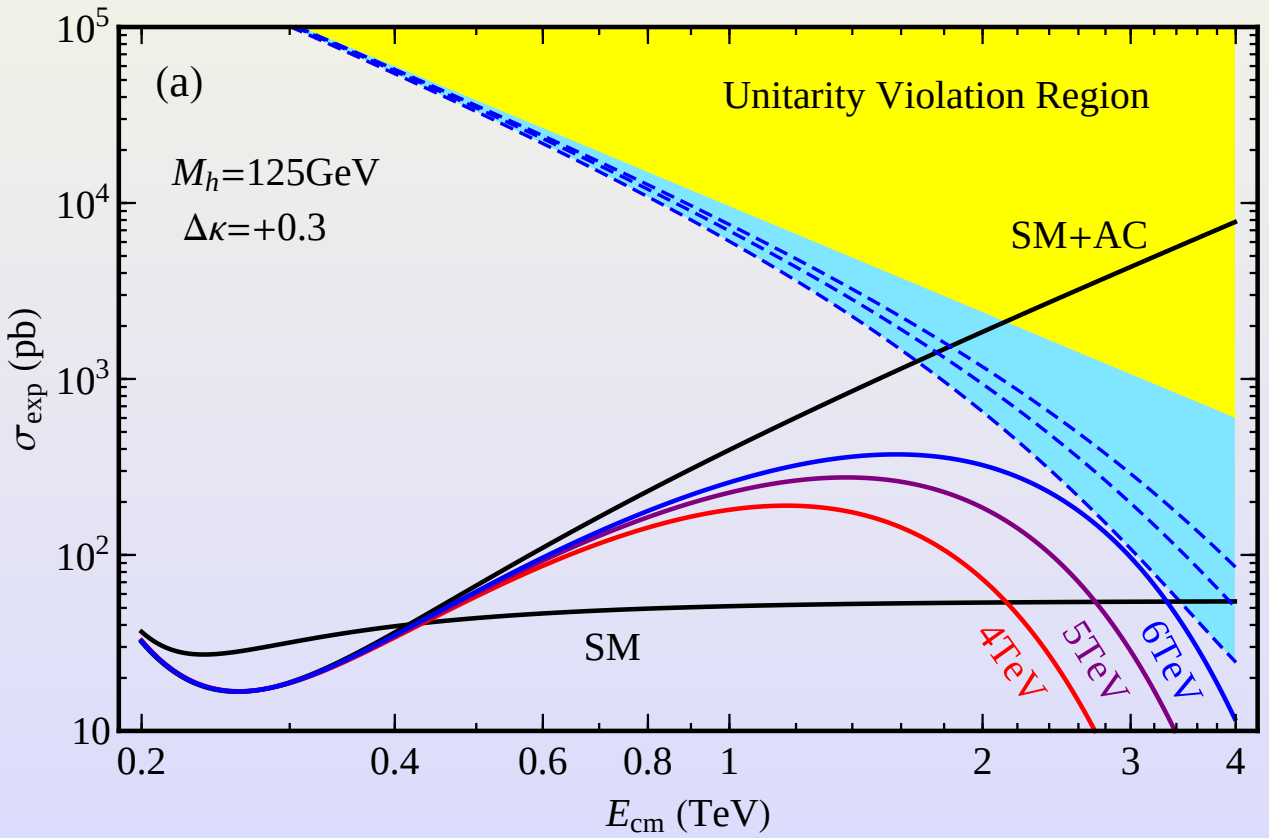
$$\Delta\mathscr{L}_H = \left(\Delta\kappa\, 2vh + \Delta\kappa' h^2\right)\left[\frac{2M_W^2}{v^2} W_\mu^+ W^{-\mu} + \frac{M_Z^2}{v^2} Z_\mu Z^\mu\right]$$

  which will destroy E^2 cancellation in WW Scattering.

- But TeV scale SDR can help to unitarize the high energy WW amplitudes below $\Lambda_{\mathbf{UV}}$, in much the same way as it does for the Higgsless SM.

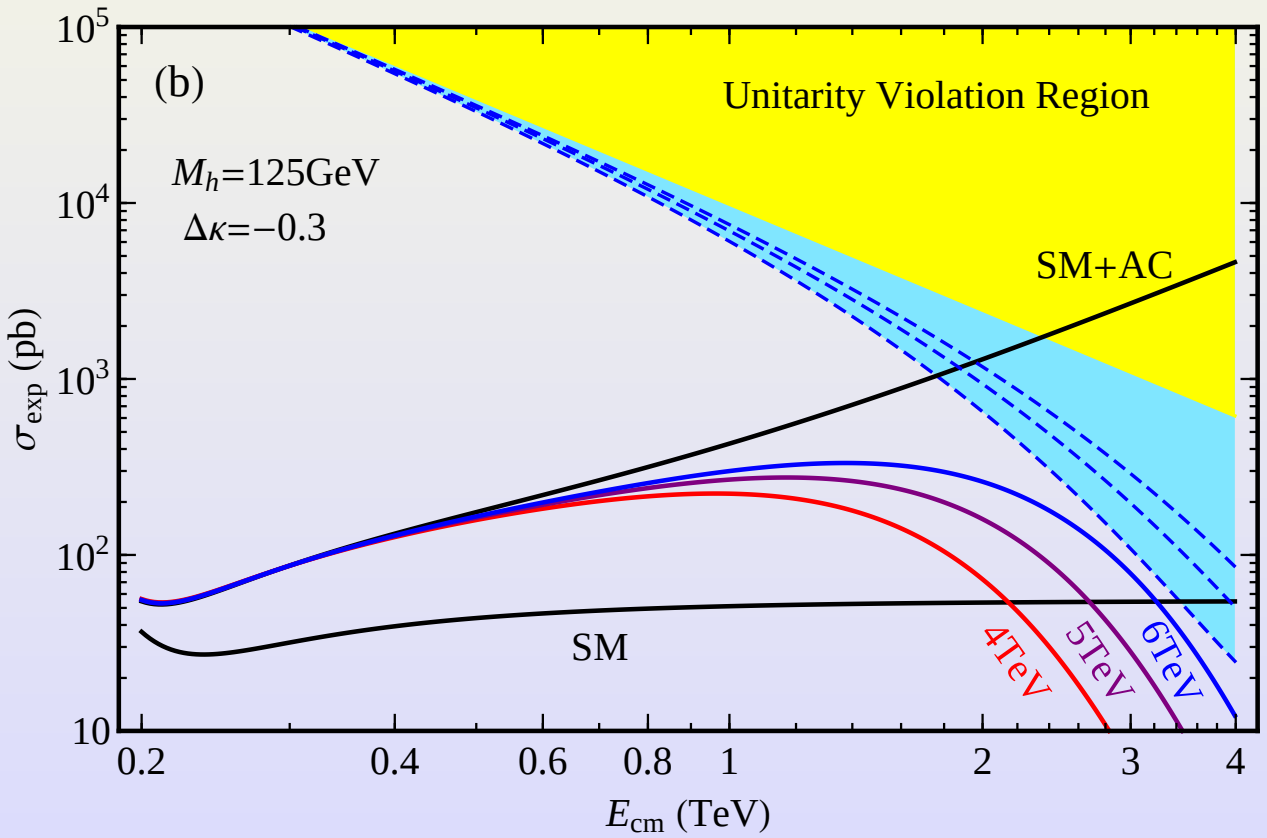
Unitary Higgsful SM under SDR: WW Scattering

- **Example-1:** $W_L^+ W_L^- \to Z_L^0 Z_L^0$ **with** $M_h = 125\,\mathrm{GeV}$ **and** $\Delta\kappa = +0.3$



Unitary Higgsful SM under SDR: WW Scattering

- **Example-2:** $W_L^+ W_L^- \to Z_L^0 Z_L^0$ **with** $M_h = 125\,\mathrm{GeV}$ **and** $\Delta\kappa = -0.3$



Summary and Outlook

- TeV Scale SDR is a new fundamental way to ensure Renormalizability and Unitarity of Higgsless or Higgsful SM !
- It provides a natural realization of explicit mass-generations via lower dimensions at high energies. It leads to Unitary Higgsless SM — can be discriminated at LHC via WW scattering !
- In the presence of a fundamental light Higgs, the TeV Scale SDR resolves the Hierarchy Problem, and ensures Unitary Higgsful SM. — Quantum Gravity also causes anomalous Higgs Gauge Couplings and can be tested at LHC !

Summary and Outlook

- Many interesting issues worth of further explorations along this direction —
- How to probe SDR at the LHC?
  WW Scattering and other processes (in preparation)
- May we understand SDR better analytically?
- Connect to Asymptotic Safety scenario (in preparation)
- How to quantize the theory + go beyond tree-level?
  Electroweak precision constraints?